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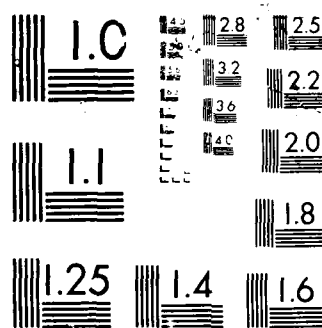   ELECTRONICS RESEARCH LAB E POLAK 11 APR 88
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NUMERICAL OPTIMIZATION, SYSTEM THEORETIC AND SOFTWARE TOOLS FOR THE INTEGRATED DESIGN OF FLEXIBLE STRUCTURES AND THEIR CONTROL SYSTEMS

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ANNUAL TECHNICAL REPORT FOR PERIOD 1986 - 1987.

1. SUMMARY

The reported research was motivated by a growing consensus that design specifications for projected controlled flexible aerospace structures, which are becoming larger and more flexible while performance requirements are becoming more stringent, can only be satisfied through an *integrated* design approach in which one determines simultaneously both structural and control system parameters.

The reported work dealt with the development of nonsmooth optimization techniques for the integrated design of flexible structures and their control systems. Nonsmooth optimization is an ideal tool for integrated design because it allows dynamic constraints and imposes no distinction between control system and structural variables.

Major accomplishment include the development and testing of an optimal control algorithm which can be used to solve both free and fixed time optimal control problems, such as the problem of moving a flexible structure, modeled by a partial differential equation, from an in initial to a final position in minimum time, while guaranteeing upper bounds on the controls and deformations of the structure over the entire maneuver; and (ii) the laying of the ground-work for the frequency domain design of finite dimensional feedback controllers for flexible structures, without resorting to modal truncation and suffering the resulting spillover effects.

2. TECHNICAL REPORT

1. Research Objectives

The broad research objective of this project is the development of an optimization-based computer-aided design methodology for the integrated design of flexible structures and their control systems. The specific areas being developed are (i) semi-infinite optimization algorithms for the integrated design of flexible structures and their control systems, (ii) optimal control algorithms for distributed systems with control, state and shape constraints, (iii)

consistent discretization techniques for use in optimal control algorithms that solve problems with dynamics governed by partial differential equations, (iii) optimization-oriented system theory, and (iv) interactive software for optimization-based control system design.

2. Significant Accomplishments

The most significant accomplishment to date is the development an extensive theory which establishes the fundamentals of nonsmooth optimization algorthms for the solution of minimax problems. This work was reported in [8]. Out of this work came also a new version of Newton's method for the solution of minimax problems [4].

In [6] we reported an algorithm for the solution of optimal control problems with ordinary differential equation dynamics, state space constraints and control constraints. Ted Baker undertook the extension of this algorithm to optimal control problems with partial differential equations dynamics, state space constraints, and control constraints. It required the development of a theory of relaxed controls and consistent discretizations for these problems, as well as a number of algorithmic innovations. Baker's doctoral dissertation is expected to be completed early in 1988. Some of the experimental results are described in [12]. The above mentioned algorithm can be used for solving optimal slewing problems involving flexible structures whose deformation must be kept within prescribed bounds during the entire maneuver, and whose actuator torques are bounded. The algorithm and associated theory will be reported in a series of papers in 1988.

Convex optimal design problems with affine parametrizations tend to exhibit severe ill-conditioning which is attributed to these parametrizations. In order to understand the reasons for this ill-conditioning we undertook a study of the rate of convergence of various nonsmooth optimization algorithms. Our first results in this area were reported in [11]. These have lead to a new class of very promising new nonsmooth optimization algorithms which are currently being evaluated.

Most current work dealing with the design of feedback compensators for controlled flexible structures is based on linear quadratic regulator theory. It has two major drawbacks. The first is that it requires approximation of a PDE model for the dynamics by an ODE model obtained by modal truncation. This leads to spillover effects which destabilize the feedback system. The second drawback is that LQR theory is a very limited design tool capable of dealing with very "soft" specifications only. In order to provide an alternative, we have developed a new computational stability test [3] and an H^∞ minimax multiloop shaping technique [9, 10]

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which can be used for the design of feedback systems with both time and frequency domain specifications. Since frequency responses of systems described by linear (one dimensional in space) PDE's can be computed by solving two-point boundary value problems involving only ODE's, they can be computed with required precision at specific frequencies, with the precision dependent on the frequency. As a result, spillover effects are avoided.

Finally, a novel approach to adaptive control was explored in [7], which describes a technique for the identification of parametric uncertainty sets and their utilization in periodic controller redesign, using a minimax, worst case approach.

3. Publications

[1]   D. M. Stimler and E. Polak , "Nondifferentiable Optimization in Worst Case Control Systems Design: a Computational Example", *Proc. IEEE Control Systems Society 3rd Symposium on CACSD*, Arlington, Va., September 24-26, 1986.

[2]   D. Q. Mayne and E. Polak "Algorithms for Optimization Problems with Exclusion Constraints", *JOTA*, Vol. 51, No. 3, pp. 453-474, 1986

[3]   E. Polak and S. Wuu, "On the Design of Stabilizing Compensators via Semi-Infinite Optimization", *University of California, Berkeley, Electronics Research Laboratory* Memo No. M86/102. Oct. 24, 1986. *IEEE Trans. on Automatic Control*, in press.

[4]   E. Polak, D. Q. Mayne and J. Higgins, "A Superlinearly Convergent Algorithm for Min-Max Problems", *University of California, Berkeley, Electronics Research Laboratory* Memo No. M86/103, Nov. 15, 1986 (Submitted to 1988 IEEE Conf. on Dec. and Control).

[5]   E. Polak and D. Q. Mayne, " Design of Multivariable Control Systems via Semi-Infinite Optimization", *Systems and Control Encyclopaedia*, M. G. Singh, editor, Pergamon Press, N.Y. 1987.

[6]   D. Q. Mayne and E. Polak "An Exact Penalty Function Algorithm for Control Problems with State and Control Constraints", *IEEE Trans. on Control*, Vol. AC-32, No. 5, pp. 380-388, 1987.

[7]   E. Polak, S. Salcudean and D. Q. Mayne, "Adaptive Control of ARMA Plants Using Worst Case Design by Semi-Infinite Optimization, *IEEE Trans. on Automatic Control*, Vol. AC-32, No. 5, pp. 388-397, 1987.

[8]   E. Polak, "On the Mathematical Foundations of Nondifferentiable Optimization in Engineering Design", *SIAM Review*, pp. 21-91, March 1987.

[9]   E. Polak and S. E. Salcudean, "On The Design of Linear Multivariable Feedback Systems via Constrained Nondifferentiable Optimization in H^∞ Spaces" *IEEE Trans on Automatic Control*, in press.

[10] E. Polak and S. E. Salcudean, "Algorithms for Optimal Feedback Design", *Proc. International Symposium on the Mathematical Theory of Networks and Systems (MTNS/87)*, Phoenix, Arizona, June 15-19, 1987.

[11] E. Polak, C. Gonzaga and J. Wiest, "Linear Convergence of Semi-Infinite Programming Algorithms", 11th Triennieal IFORS Conference on Operations Research, Buenos Aires, Argentina, August 10-14, 1987.

[12] T. E. Baker and E. Polak, "Computational Experiments in the Optimal Slewing of Flexible Structures", *University of California, Berkeley, Electronics Research Laboratory* Memo No. M87/72, Sept. 1, 1987. (To be submitted in expanded form to SIAM J. Control and Optimization).

3. PARTICIPATING PROFESSIONALS

The project included Prof. E. Polak, Prof. D. Q. Mayne, visiting from Imperial College London and five students: T. Baker, Y-P Ham, L. He, S. Salcudean, and T-L Wuu, with funding supplemented by NSF and ONR grants. Mr T-L Wuu obtained his Ph.D. in 1987, with the thesis: "DELIGHT.MIMO: An Interactive System for Optimization-Based Multivariable Control System Design".

4. INTERACTIONS

We have been interacting with the NASA Langley Research Center on the SCOLE experiment. The results reported in [13] were presented at the 1987 SCOLE Workshop, in Colorado Springs, Co. We have had also a small amount of personal interaction with Dr. Khot of WPAFB on optimization-based design of flexible structures. We have continuing interaction with Prof. D. Q. Mayne, a Fellow of the Royal Society, of Imperial College, in the area of optimization algorithms and CAD software development.

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